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Bedload Measurement in Rivers Using Passive Acoustic Sensors

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Abstract

Two types of acoustic bedload sensor have been tested by the Norwegian Water and Energy Directorate (NVE) to determine their ability to measure bedload transport in rivers. The first generation sensor was tested in the field and laboratory. It measures acoustic signal in a narrow frequency band (centre frequency 70 kHz) and outputs the amplitude as a single value every second. This model was installed at field stations in the Nigardsbreen glacial river in 1998, in the river Gråelva in 1999 and in Bayelva in Svalbard in 2000. The other model, a multi frequency ("2nd generation") sensor, was tested extensively in a flume. It outputs a frequency spectrum with a theoretical range of 0-1000 kHz divided into 512 components, each corresponding to a 2 kHz wide band. Both models measure the acoustic signal of bedload impacts on a plate fixed to the river bed. Flume studies showed that the sensor signal is highly influenced by the sediment grain size. This effect indicates that it is not possible to calibrate a sensor operating on a single frequency. Sensor records from the field stations demonstrated that it is nevertheless able to depict the pulsating and discontinuous pattern of bedload movement and may possibly identify the effect of clusters. During periods when the bedload grain size is not subject to abrupt changes, the short term variations in sensor signal are positively correlated with bedload flux.

In order to address the problem that the acoustic signal is influenced by grain size, it was necessary to develop a multivariate model, utilizing multiple frequency variables. A series of flume experiments was designed to calibrate and validate a model, and in excess of 450 runs were carried out. Most of the experiments used a water velocity of about 2 m/s and grain sizes ranging from 3 to 40 mm. The model was based on the acoustic measurements from the multi frequency sensor. It was able to quantify the sediment flux irrespective of temporal changes in grain size distribution. Data analysis comprised *Principal Component Analysis (PCA)* and *Partial Least Squares Regression (PLS-R)*. PCA was used to explore the raw data (frequency spectra from the sensor) particularly with regard to trends and clusters. The results were thereafter compared with bedload transport rates and bedload fractions to see if, and how, they are related. PLS-R was used to develop computational models for estimating bedload properties from the acoustic spectra. It was concluded from the PLS-R analysis that it was possible to find a linear model which describes the bedload transport in terms of acoustic signals. The model is able to compensate for changing grain size. It was also found that the transport of mixed fractions could be modelled in the same manner, although confirmation requires further flume studies.

Introduction

Bedload transport data is important for many aspects of river management and it is desirable to improve the methods for measuring and studying bedload transport processes in rivers. The most important need for bedload data in Norway has been related to the construction of power plants and the assessment of environmental impacts on downstream river reaches. A majority of Norwegian power plants divert water via a number of different intakes. During the construction period it is necessary to estimate the bedload of each of them. This is done to select the locations for sand traps and sedimentation basins within the hydropower scheme (Bogen 1989, Bogen & Bønsnes 2001).

The difficulties involved in directly measuring bedload have called for alternative field methods. Measurements of annual suspended load and bedload in the meltwater river from the Nigardsbreen glacier have shown a fairly constant ratio of 1:1 through a 30 yr period (Bogen & Bønsnes 2003a). The bedload volumes delivered to the intakes of the power plants were also estimated in this way, using the appropriate ratios for each glacial area.

River reaches downstream from hydropower intakes are often subjected to environmental impacts, and channels from which water has been diverted may adapt to the new regimes of reduced water discharge and sediment load. Monitoring is desirable in this context as such changes may affect fish habitats and also reduce the volumes of gravel that may be extracted from river bed. In response to this, field testing of acoustic bedload sensors was started in Norwegian rivers in the late 1990s.

Acoustic signals are relatively easy to measure, and acoustic sensors are reasonably robust and fairly non-intrusive. The introduction of sensors therefore seemed a promising approach for obtaining more reliable data and thereby increasing our understanding of the bedload transport process. On the other hand, the interpretation of acoustic measurements in terms of bedload properties was not straightforward. A multitude of physical properties of the sensor system influence the acoustic behaviour, for example properties of the material, internal plate tension, size and weight. Sensor output also incorporates a large noise component. The use of acoustics has been investigated for several decades as a promising technology for in situ measurements of bedload transport (Richards and Milne 1979, Banziger and Burch 1991, and Rickenmann et al. 1997).

This paper reports the results of testing passive acoustic bedload sensors in field and laboratory studies. A preliminary report from the study was given by Bogen and Møen (2003). The first part of the present paper discusses the results from field installations. In the second part, the behaviour of a broad spectra acoustic sensor system is analysed and calibrated in flume studies using *Partial Least Squares Regression (PLS-R)*. Some of this work was carried out by two research students (Ade and Zuta 2006). The first flume experiment results gave linear relations between bedload transport in g/s and acoustic signal for individual grain size intervals. In the present paper, the flume experiment results are discussed after the earlier field work studies have been presented.

Field experiments with 1st generation NVE-sensor

When NVE began exploring the use of passive acoustic monitoring for measuring bedload transport, a slightly modified version of a commercially available sensor used in the oil industry was employed. This sensor was originally developed to quantify the sediment particle flux in oil pumped up from wells. In that application the sensor was clamped onto a pipeline, preferably close to a bend or constriction. The acoustic energy generated by collisions between particles entrained in the oil and the pipe wall is picked up by the sensor. Deployment in a river demanded an alternative mounting principle;

the sensor was mounted underneath a 50x50 cm plate and the sediments tumbled past it on the top side (Figure 1).

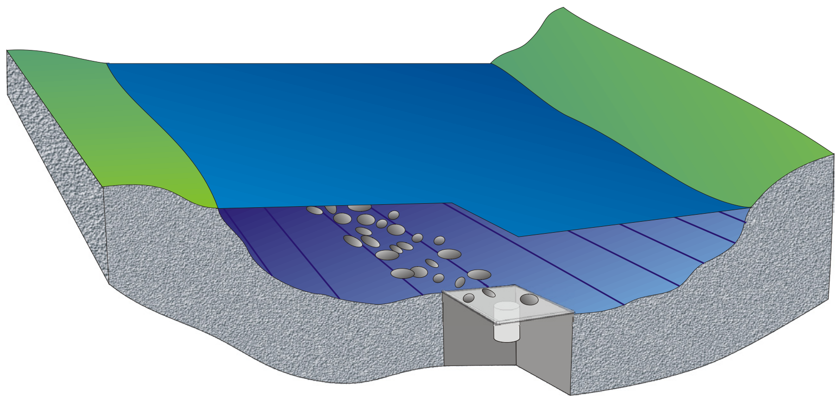

Figure 1. Principle of sensor mounting in a river. The sensor plate is levelled with the river bed, and the acoustic sensor is mounted underneath.

The sensor has a high sensitivity compared to commercially available accelerometers. Even small amounts of fine sand give a significant response in sensor output, well below the detection limit found using off-the-shelf accelerometers. The internal signal processing is nevertheless rather rudimentary. A band-pass filter is applied to the acoustic raw signal, allowing a narrow frequency band centred at 70 kHz. The average amplitude of the resulting signal is output every second. This single acoustic component is used to indicate temporal variation in bedload transport. Some simple attempts to calibrate the sensor showed that for any homogeneous or fixed grain size distribution, the repeatability of the sensor is good and it shows a semi-logarithmic relationship between acoustic signal strength and bedload flux. Calibration should thus be easy to accomplish, but unfortunately the sensor signal is very sensitive to sediment grain size. This particular sensor and plate configuration proved to be most sensitive to sediments in the 1-2 mm range, with a considerable reduction in sensitivity to sediments outside this range, both larger and smaller fractions (Figure 2). The reason why sensitivity is highest for a particular grain size is probably related to shifts in frequency rather than impact energy. This is more thoroughly explained later in this article.

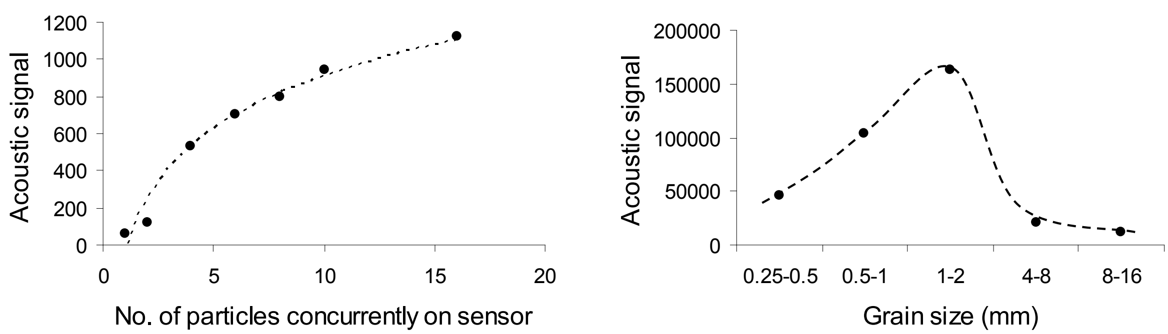

Figure 2. Left: Acoustic signal as a function of increasing sediment flux (4-8mm grain size). Right: Acoustic signal to different fractions being fed at a flux of 100g/s.

A single acoustic component produced in this manner is, thus, insufficient to quantify the transport rate in a natural river where sediment grain size distribution will change over time. This indicates that additional variables might need to be included in the calibration to accommodate for such a temporal variation in grain size distribution. Despite this, the sensor gives a good indication of patterns and trends in the bedload transport. Assuming the fraction composition does not change abruptly, the short term transport rate variation is positively correlated to variations in sensor signal. The instrument is reasonably easy to deploy in the field and required little or no maintenance. It is important that the sensor is installed in a location where no deposition of sediment occurs.

NVE installed three sensors of this type at field stations: in the Nigardsbreen glacial river in 1997, in the river Gråelva in South central Norway 1999 and in Bayelva in Svalbard in 2000. The Nigardsbreen station was discontinued 1999 because of major channel changes caused by a glacier advance. The latter two are still in operation (as of 2007).

Bayelva is located near Ny Ålesund on Svalbard in the high Arctic. Most of the sediments are supplied by glaciers or by erosion in the glacier forefield. Sediment transport and water discharge are measured at a Crump weir near the river outlet into the fjord. Suspended sediment transport have been monitored at this station from 1990 (Bogen and Bønsnes, 2003b). The river crosses several sandurs between the glaciers and the monitoring station. The river bed sediments are dominated by angular gravel and cobble fractions derived from sandstones. Descriptions of the installation and bedload sampling programmes can be found in Bogen and Møen (2003).

Experience has shown that the sensor records are able to depict the pulsating and discontinuous pattern of bedload movement by means of the maximum and average values at 1-minute intervals (Figure 3). The shape of the curves appears to reflect the processes affecting the bedload movement. When a continuous flow of bedload particles strikes the plate the curves follow each other smoothly. This situation often occurs during low water discharges and most probably is caused by a steady movement of sand along the bed. As water discharge increases, the maximum acoustic amplitude often deviates markedly from the mean amplitude. This could correspond to a situation with incipient movement of gravel or cobble fractions.

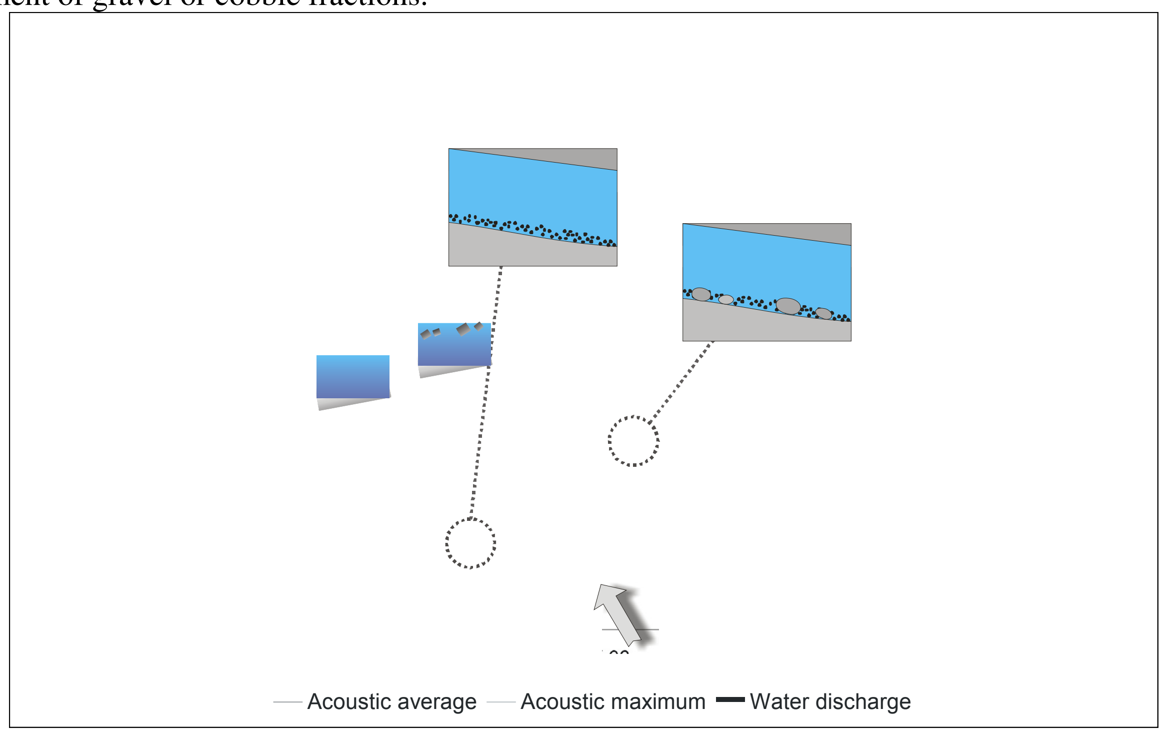

Figure 3. Records of the average and maximum acoustic signal at one-minute intervals in Bayelva, 27 June to 5. July 2003. Symbolic illustrations of continuous and discrete particle flow are inserted.

During the flood event culminating on 29 June 2003, the bedload transport was more intense on the rising limb of the water discharge than on the falling one. However, a sudden transition was observed on a falling and relatively low water discharge on the 1 July around 01:00, probably recording a pulse of bedload transport caused by a sudden flux of material (indicated by arrow in figure 3). Such an event may be attributable to the collapse of a river bank or adjacent moraine slope, or possibly the release of material from a cluster. Sediments that are delivered in this way will most often be composed of a mix of gravel and sand and they impose a change in grain size.

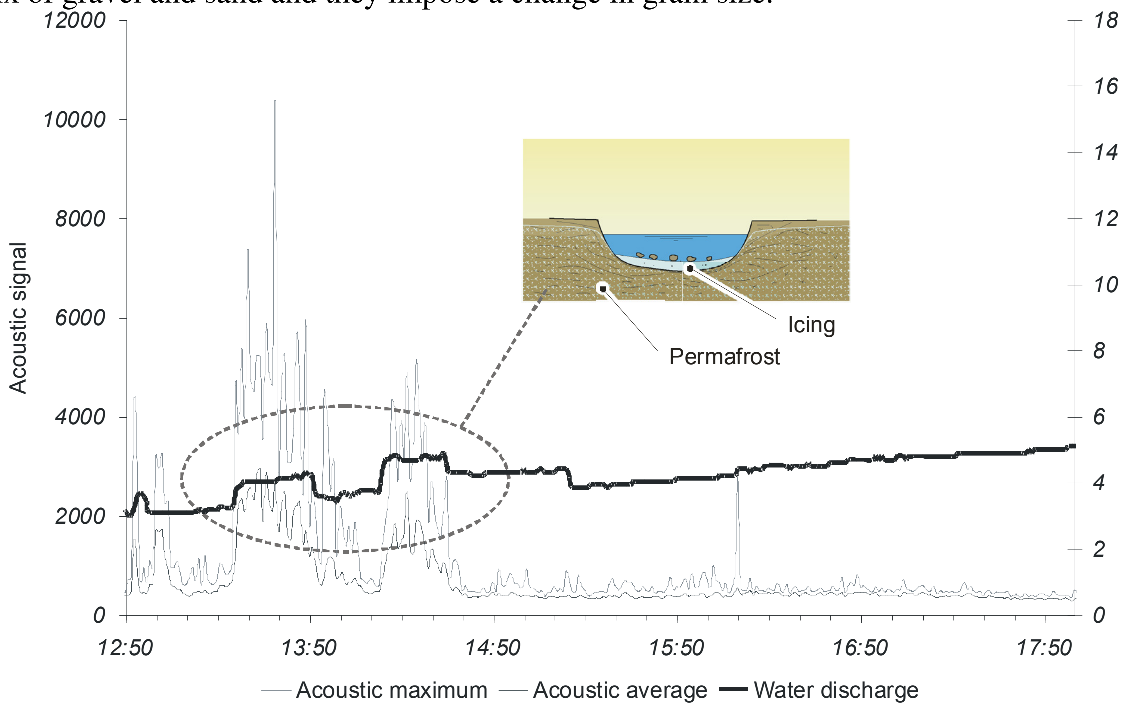

Figure 4. Average and maximum acoustic signal calculated for 1-minute intervals, and water discharge in the river Bayelva (20 June 2003).

Svalbard is a permafrost area that experiences physical conditions differing from those in more temperate regions. The beds of high arctic rivers are still covered by a layer of ice during the early part of the melting season. When the melting starts in June, sediments may be introduced into the rivers from collapsing banks or adjacent slopes. This material falls onto the ice-covered bed where there is almost no friction and even small increases in water discharge have been observed to move considerable amounts of coarse sediment. It is very likely that the incident on 20 June 2003 shown in Fig. 4 is a recording of such an event. The water discharge varies in an irregular manner; the fluctuations during 13:30 – 13:50 and 14:10 – 14:30 were most likely caused by temporary ice damming upstream of the weir. Unexpectedly high intensity acoustic signals occurred during the event, probably caused by bedload transport enabled by the reduced friction. It would be very difficult to monitor this situation with manual sampling.

In November 1999 another sensor was installed, this time in the lowland river Gråelva in central Norway. The sensor and the corresponding plate were built into the weir of the water discharge monitoring station. The records from this river differ from Bayelva in that most of the time acoustic response tends to be close to zero. Even during incidents with strong signals, the maximum acoustic response tends to be much greater than the average value at 1-minutes intervals. This is interpreted as discrete movement of particles. The Gråelva is situated in a clay area where the availability of sand and gravel is limited to a sparse supply on river bars. This mobile sediment supply can be quickly exhausted, effectively restricting bedload transport to the early part of a rising discharge stage, Fig. 5.

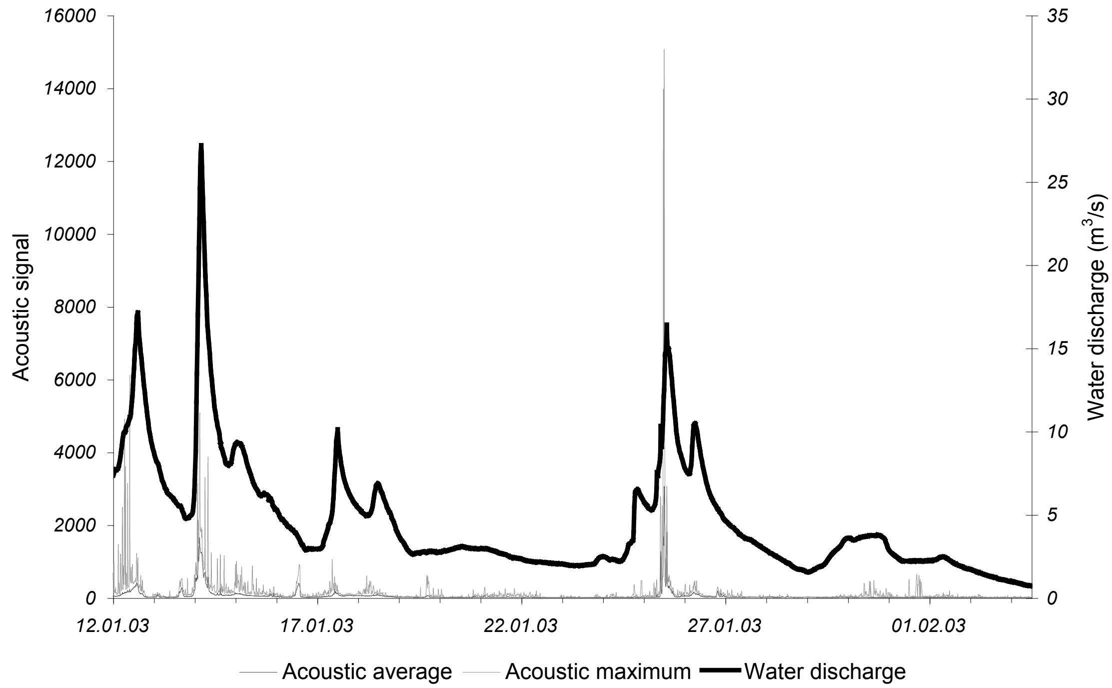

Figure 5. Average and maximum acoustic signal calculated for 1-minute intervals and water discharge in the river Gråelva at Børstad, 12 January – 3 February 2003.

2nd generation NVE-sensor

The frequency domain of the acoustic signal was analysed to investigate the potential for calibrating the instrument to compensate for changes in grain size. A hypothesis was formulated suggesting that information relating to grain size may be found in the frequency patterns. This was partly based on the occurrence of non-linearity in acoustic intensity in response to grain size. This idea was further supported by the experience that the human ear is able to discriminate between sounds generated by different sized particles, despite an apparently high degree of noise.

By 2002, the manufacturer had developed a new generation acoustic sensor with a large dynamic range and embedded frequency analyser. The study and calibration of this new generation sensor is the focus of the remainder of this paper

This new sensor model has a similar physical design as the earlier one and the same industrial robustness. It has a theoretical frequency range of 0-1000 kHz producing a frequency spectrum with 512 components, each corresponding to a 2 kHz wide band. The signal amplitude is throughout this paper described as *acoustic signal*. Although not a dimensionless unit per se, the values should be regarded as an index related to the acoustic energy rather than a specific energy unit. More specifically the acoustic energy is the acceleration of the sensor head. The signal amplitude and range it self is highly system specific and small alterations in plate configuration, bolt torques etc might change the absolute values. When used in calibration and models, all values are normalized, thus the actual values are not important.

Tools and methods

Employing a frequency spectrum as a basis for the analyses provides a hyper dimensional variable space but with a high degree of co-variation within the variables. The tools chosen to explore the acoustic data are two related multivariate data analysis methodologies; *Principal Component Analysis (PCA)* and *Partial Least Squares Regression (PLS-R)*. Such methods were successfully applied to systems related to particle classification by Halstensen (2001).

PCA is used to explore the raw data (frequency spectra) from the sensor, looking for trends and clusters. These were examined to determine if they are related to known bedload transport rates and bedload grain sizes used in the flume runs. In essence, PCA separates the data matrix ("X") into a structured part and a noise part. It does this without reference to the variable of interest (bedload), in multivariate terminology named the "Y" matrix (Esbensen 2002). The PCA technique is primarily used to give a "proof of concept", i.e. show that the information and variation of interest really is present in the raw data.

PLS-R has been used throughout this project to develop computational models for estimating bedload properties from the acoustic spectra. PLS-R seeks to find a linear model describing the response variables (bedload flux and fractions) in terms of the observed variables (acoustic).

Test flume

A full-scale test flume was built in 2003, representing a simplified river channel (Figure 6). The flume is 0.5m wide and 3m long. The flow of water is fully controllable, as is the sediment feeding. Natural river-sediment sieved into homogeneous fractions was used in all the experiments. Constant sediment feeding is provided by a computer-controlled conveyor belt, feeding pre-weighed portions of sediment into the water flow at a constant rate. The sediment is introduced approximately 3 m upstream of the sensor, allowing the material to sink and move in contact with the bed before reaching the sensor. The sensor is mounted under a 1cm thick 50x50 cm steel plate. The sensor plate spans the whole width of the flume, guaranteeing that all the test sediment passes over the sensor.

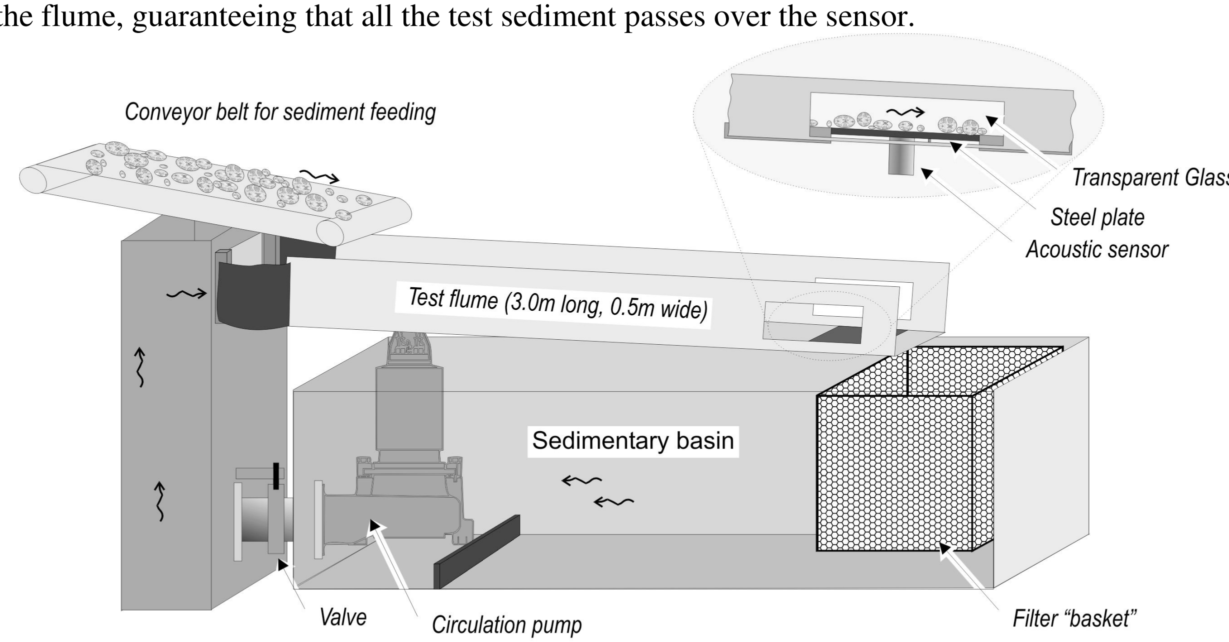

Figure 6. Principal layout of test rig.

Experimental design

The main objective in the experimental design was to develop a model based on the acoustic signal which could quantify the sediment flux irrespective of different fractions or fraction compositions. Also, it was important to establish the robustness of the method, both in terms of repeatability and the effect of changes in sediment properties.

All in all, in excess of 450 experiments have been carried out in the test flume. About 400 of these used coarse material (3-40 mm) while the rest involved mainly two sand fractions (0-0.5 mm and 0.5-1.0 mm). Two types of coarse sediment were tested, one of highly rounded material and one of angular type. A water velocity of ~2 m/s was employed in these experiments.

Most groups of experiments were conducted twice to produce independent test set data. All the main models have thus been fully test set validated. The test data sets are not extensions of experiments but are produced in separate test runs, independently of the calibration data. This introduces an added level of stochastic noise to the data, which makes the test conditions more realistic. This approach gives a good validation of the model, but considerably increases the time and labour used in producing the data. Table 1 summarizes the different experiments.

Table 1. Summary of experiment designs in flume studies,

Design	Objective	Sediment size (mm)	Bedload flux (g/s)	No. of exp.
A	calibration of sediment flux using different but homogeneous fractions	angular 3 – 40.5	10 – 450	57 + 57
B	reproducibility test, compared to A	angular 3; 4.5; 8.5	70;150;250;350	16 + 16
C	calibration of sediment flux using non-homogeneous, mixed factions	angular 3;4.5;8.5;12;18;27;40.5 in 20%/80% mixes	10; 40; 250;450	32
D	calibration of sediment flux using different but homogeneous fractions	rounded 8.5;18;40.5	10; 20; 40; 70; 150; 250; 350; 450	24 + 24
E	reproducibility test, compared to D	rounded 8.5;18	10; 150; 350; 450	16 + 16
F	calibration of sediment flux under varying and partly turbulent flow conditions;flow velocity: 1.4, 1.7, 2.0, 2.6 m/s	rounded 8.5;18	10;150;350;450	16 + 16
G	as “D”, but with a different sensor plate geometry.	rounded 3;4.5;8.5	10; 150; 250; 350	16 + 16
H	study of sensor response of ice-in-water vs. sediment	ice blocks 7-20kg	n/a	10

Experiments A-H were conduced as part of an MSc thesis by Ade & Zuta (2006). A detailed report of all these tests can be found there. In the present paper only experiments A, C and G are discussed.

General acoustic findings

To exemplify the general acoustic behaviour of the sensor system, the average acoustic signal recorded by the sensor at 1 s intervals was plotted against sediment flux (Figure 7). All the design “A” test runs were included. The term *average acoustic signal* is here used to signify the sum of all frequency components amplitude, divided by the number of components (512). It is seen that for any particular grain size fraction, the increase of acoustic response is seemingly linear to the sediment flux It is interesting to note that the sensor system yields higher responses for finer sediments than for coarser material. The strong effect that grain size has on the total acoustic response clearly demonstrates that a sensor deployed in a river system with varying bedload grain size distribution can not be calibrated using a single acoustic component.

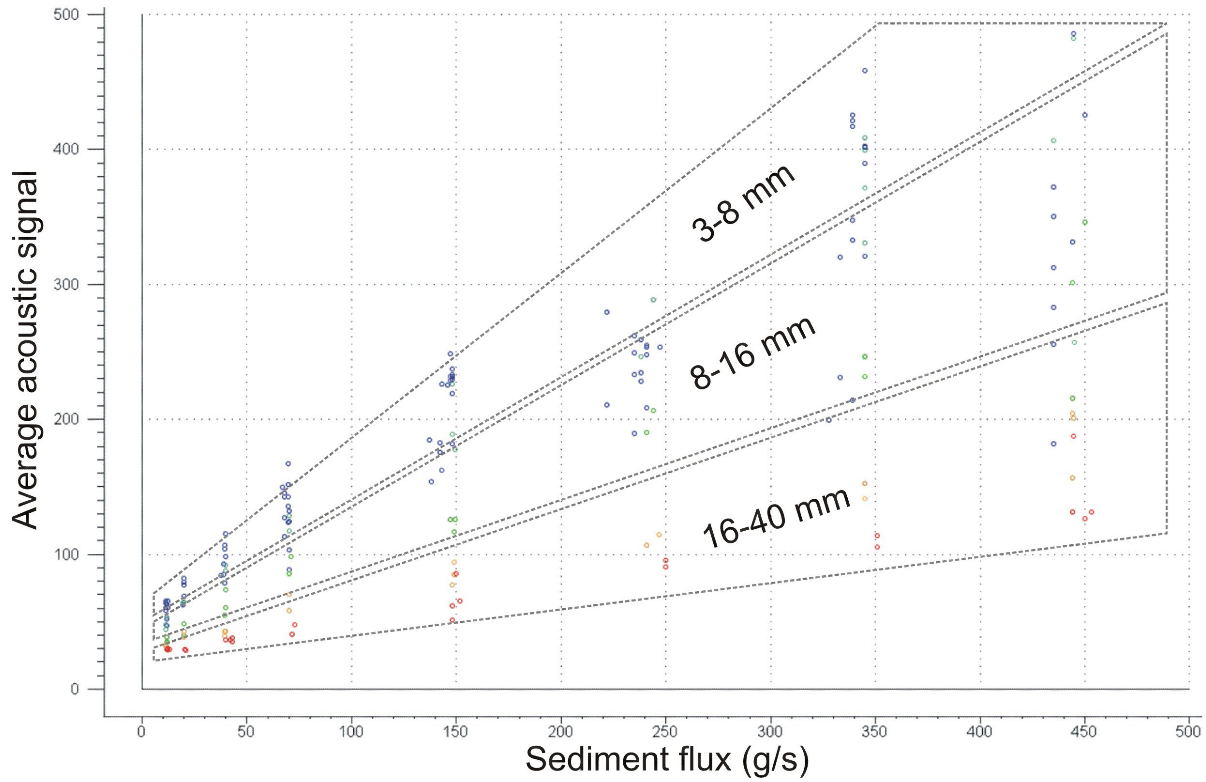

Figure 7. Variation of the average acoustic signal with sediment flux for different grain fractions.

The effect of coarse material giving less response than finer material is believed to be system-dependant. It is known that this particular sensor system is less sensitive to frequencies below 30 kHz. As the frequency plot in figure 8 shows, coarse material gives a higher response in lower frequencies.

Figure 8 shows all the frequency spectra of test design “A” sorted by fraction and sediment flux. As a general observation, the dominant frequency tends to fall as the sediment grain size increases. This tendency is most pronounced in 30 lowest frequency components (0-60 kHz). Although the flux varies within each grain size interval, only the amplitude of the spectrum changes, not the shape. This clear relationship between frequency and grain size is less pronounced in higher frequency bands.

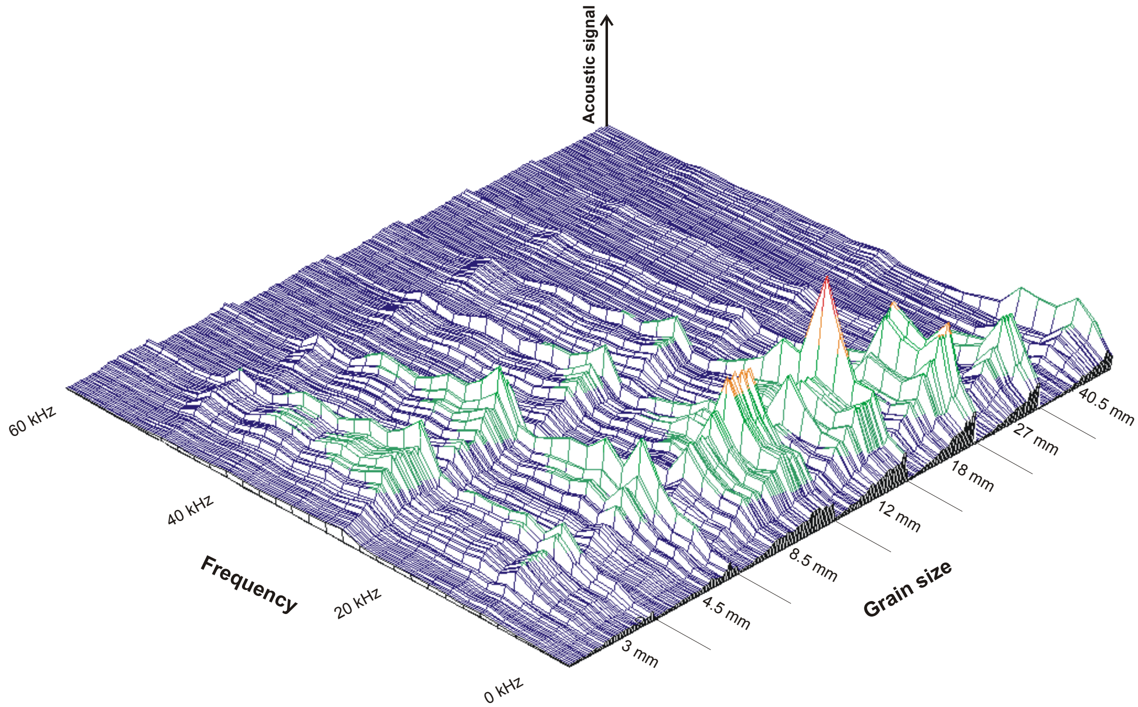

Figure 8. Frequency spectra from the “A” design. Within each grain size fraction, bedload fluxes were varied in the range 10 – 450 g/s.

Model calibration

A large number of PLS-R based models were calibrated and evaluated by Ade & Zuta (2006) based on test designs “A” – “G” (Table 1).

Roundness of sediment particles may affect the acoustic behavior of the system due to the difference in pattern of movement. A number of test-runs were carried out to explore the difference between well rounded and angular material. At any particular site one can expect the degree of roundness to be constant over time. As such, the calibration does not have to consider roundness as a factor, but a calibration made on well rounded material can not necessarily be deployed in an environment with angular material. Test design A and D are basically identical except for sediment angularity. Comparing the results of A and D shows that both types of material can be equally well calibrated, but - as stated above - not interchanged.

In this paper we will discuss three of the test designs; The “A” design, with 7 different but homogeneous fractions, The “C” design using mixed fraction material and the G design using an alternative plate geometry.

Calibration with homogeneous fractions – “A” design

A multivariate PLS1 model was calibrated with a dataset derived from 7 different fraction sizes and 8 different bedload fluxes. The permutation gives 56 individual test runs. These 56 tests were conducted twice to produce an independent test set for model validation. For each test run, the acoustic spectra were averaged and thus combined to one “sample”. The model is based on 200 acoustic components of 2 kHz covering the 0-400 kHz frequency range. Two samples in the highest sediment flux range were considered outliers and excluded from the calibration and validation.

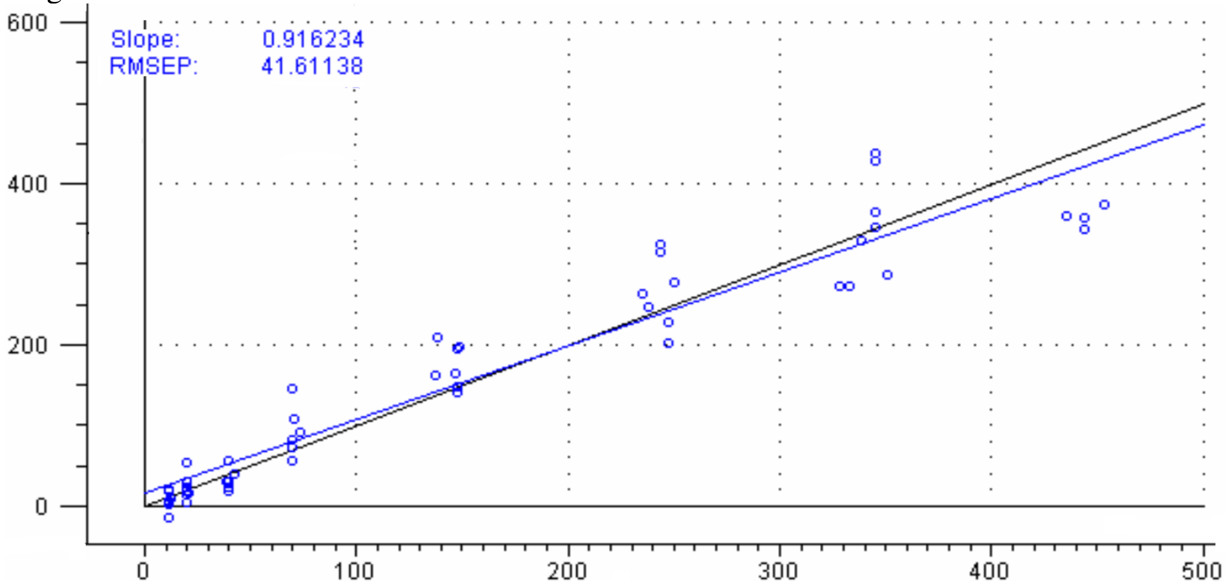

Figure 9. Validation of PLS1 model of total bedload flux. Known bedload flux as fed into test rig *vs.* flux as predicted by model.

The result shows that the PLS1 model compensates for the non-linearity of the acoustic response with respect to grain size (Figure 9). A slight logarithmic tendency in the predicted values can still be perceived. This is consistent with earlier finding of a logarithmic relationship between total acoustic responses versus sediment flux. So far the data has not been pre-treated, and the model fit might be improved by experimenting with some sort of pre- or post-treatment.

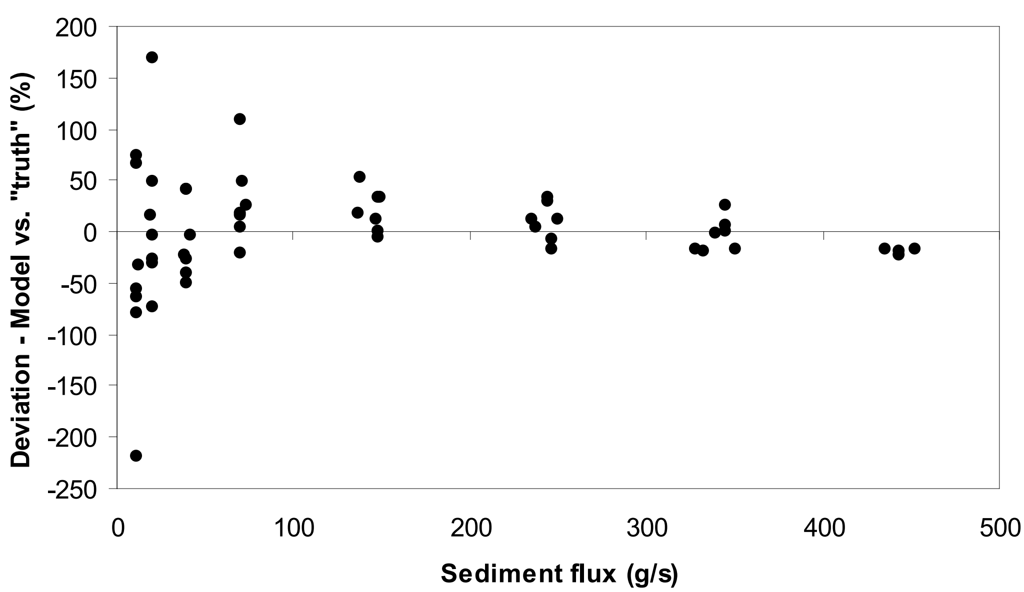

Figure 10. Error of predicted values expressed in percent of true value.

Figure 10 shows the error of prediction as percentage of true value. The error of prediction is relatively high for sediment fluxes below 100 g/s, but at higher fluxes the model performs adequately. To a large extent the error can be decreased by averaging the model result over longer time intervals. Two factors are assumed to contribute to the increased error for lower flux rates. First, assuming a constant uncertainty (e.g. RMSEP = 41g/s as found in figure 9), the proportionate error will obviously increase for small flux rates. Second, a large number of particles (as with high flux rates) gives a "natural" averaging thus reducing the error. Experiments using sand fractions support this interpretation by showing result sets with considerably less scattering even for smaller flux rates.

The clustering of samples of different size fractions run with the same sediment flux indicates that pre- or post-treatment can improve model accuracy. PLS being a linear regression method can not fully compensate for logarithmic or other non-linear tendencies in the raw data

Mixed fractions –"C" design

Although the "A" design incorporated 7 different grain-size fractions, for any particular test run the grain size was kept constant. The "C" design used 20/80% mixes of two different grain sizes. Eight different permutations of grain sizes were employed at 4 different fluxes, giving a total of 32 runs. Time and practical constraints did not permit production of a separate test set. The calibration was thus cross-validated and the performance cannot be compared directly to the "A" model.

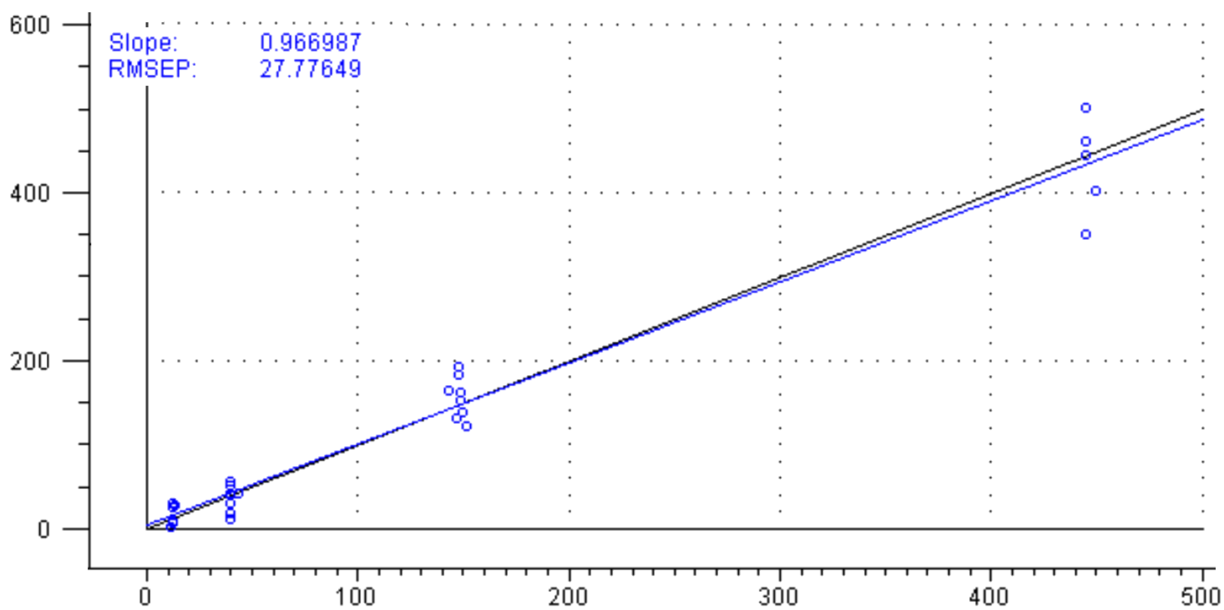

Figure 11. Validation of PLS1 model of total bedload flux for 32 mixed fraction compositions. Bedload flux as fed into test rig vs. flux as predicted by model.

Despite this use of cross validation, Fig. 11 indicates that mixtures of grain sizes can also be modelled, though a more thorough calibration would be needed to confirm these findings.

Alternative sensor geometry –"G" design

In an attempt to improve the signal-to-noise ratio, an alternative sensor plate was tested. The plate has four protruding fins placed slantwise, see Fig. 12. The rationale for experimenting with this design was that earlier observations revealed that even coarse fractions saltate at high water velocities. This leads to a reduction in impacts and consequently acoustic response. The fins on the plate surface cause turbulence, thus generating more impacts between sediment and sensor plate and direct impacts with fins.

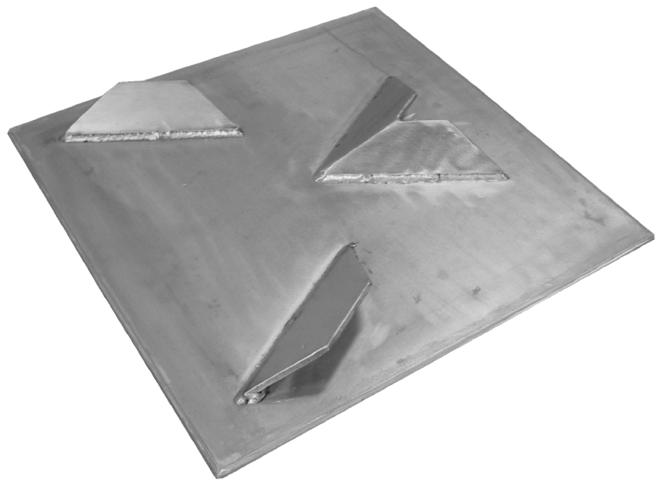

Figure 12. Experimental design of sensor plate. Protruding elements are approximately 40 mm high and welded at a slant angle of 30° both in horizontal and vertical plane.

Experimental PLS1 calibrations using the same material both on the flat sensor plates and the design shown above give no clear indication that one is better than the other. During practical operation though, the coarse material had a tendency to accumulate on the experimental plate, which could potentially impair the measurements. The present conclusion is that a non-flat sensor plate introduces unnecessary uncertainties which are not offset by the potential benefits.

Calibration to detect grain size

Most of the calibrations and experiments aimed to calibrate the system with respect to the total bedload mass. In addition, a few experiments were performed with focus on identification of grain size distribution of bedload. Halstensen and Esbensen (2000) calibrated a multivariate model based on acoustics for prediction of powder particle size distribution. These findings might be transferred to bedload grain size prediction.

To a certain degree, the system could be calibrated on the “A” dataset, classifying each of the homogenous grain sizes. Prediction for grain sizes less than 18 mm was relatively poor, and the model was unable to discriminate between fractions below this size. Prediction of coarser fraction was clearer. It was somewhat surprising that prediction of grain size did not perform better. Principal Component Analyzes (PCA) has previously shown that even different sand fraction can visually be separated in plots solely based on the acoustic signature.

The investigation did not extend to mixed grain sizes and their classification, so a final conclusion of the prospect of classifying grain size composition can not be given at this stage. The fact that the bedload mass calibration is capable of compensating for different fraction sizes indicates that the information is present in the raw data, and thus can be extracted to some degree. The full evaluation of these experiments can be found in Ade & Zuta (2006).

Field readiness and cost

The methods and tools used in this article, related to 2nd generation NVE sensor will need some modification before it can be deployed in field. The sensor, "ClampOn DSP Spectrum Analyzer" from ClampOn, Norway (*www.clampon.no*) is a robust and field-ready device. The data acquisition platform is currently not developed to the same level. It is based on a standard PC with manual operation of a rudimentary data storing software. The data analysis (calibration and prediction) are conducted manually and in batches using the statistical software package "The Unscrambler" from Camo Software AS, Norway (*www.camo.com*).

The method deployed in this project is in no way restricted to use with these specific products. We have, for example, successfully used standard miniature accelerometers from Brül & Kjær together with PC-based data acquisition hardware and software for National Instrument. This configuration was used in parallel to the ClampOn sensor and gave comparable results.

To calibrate the system and develop the chemometric model is a manual and knowledge-based process where *The Unscrambler* might be an appropiate program.. When a chemometric model is established, it can be implemented with relative ease in any computer language, and be run without need for a powerful computer platform. An advanced data logger or general purpose microcontroller could perform the task, both for data acquisition and model execution. An example of such a device could be the Xpert from Sutron Corp. (*www.sutron.com*). This device is field-ready, will have the computational powers and the possibility to be extended with the required software.

As a final field-ready concept is not at hand, an estimated cost cannot be given at this time. Based on previous experience, the cost of site engineering, infrastructure, model calibration and system deployment is a larger cost-contributor than the acoustic sensor system.

Conclusions

Two types of acoustic bedload sensors have been tested in field and laboratory experiments to determine their ability to measure bedload transport in rivers.

The first generation sensor system makes use of a single acoustic variable. This variable is influenced both by sediment grain size and sediment transport rate, and therefore it cannot be calibrated in rivers with temporal changes in bedload grain size composition. Such changes are, however, a common phenomena in many natural rivers. This sensor was nevertheless found to give a good characterisation of patterns and trends in bedload transport.

Acoustic records acquired at field stations in the rivers Gråelva and Bayelva revealed that abrupt transitions associated with pulses of bedload transport could be detected. Events due to sudden collapse of river banks or moraine slopes or release of material from clusters can thus be monitored.

To solve the problem associated with the use of a single acoustic variable, a multi-frequency system was applied. To test the feasibility of such a system, 450 individual experiments were carried out in a flume. Using a multivariate data analysis (*Partial Least Squares Regression - PLS-R)* a linear model was found to describe bedload transport in terms of the observed acoustic signal. The model was able to compensate for changing grain-size.

The field studies suggest that passive acoustic sensors offer the possibility of characterising the bedload in various river types and in this way can provide more information about processes that are specific for various sedimentological environments. Glaciers supply large amounts of coarse sediment for bedload transport in the river Bayelva, whereas the availability is limited in the Gråelva. The acoustic sensor is able to characterise this difference, and to record the increased flux that may derive from various sediment supplying processes such as bank collapse, slides or release of material from bed clusters.

The reason for the availability-controlled transport in Gråelva is the sparse occurrence of gravel and sand. Many such rivers are vulnerable to large landslides triggered when an armouring layer of gravel or sand is eroded. This is a prime example of the potential practical value of bedload monitoring. Another relevant application is the maintenance of river bed quality in regulated rivers, where it is often necessary to flush gravel beds to preserve fish habitats. Further studies and development of this acoustic method can improve our understanding of bedload processes and considerably contribute to river management.

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